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The effect of common Dutch white clover (*Trifolium repens* L.), as a green manure, on biomass production, allometric growth and foliar nitrogen of two willow clones

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Abstract

There is potential for soil erosion and non-point source pollution during the establishment of short-rotation woody crops (SRWC) in northern climates as a limited amount of cover remains on soils from the time of site preparation until SRWC occupies the site early in the second growing season. To counteract these impacts, green manure crops may be established and turned under early in the growing season. The effects of a green manure crop, white clover (*Trifolium repens* L.), on growth rates, biomass allocation, and foliar nitrogen concentrations of two willow clones (*Salix sachalinensis* and *S. discolor*) were compared in a field experiment to nitrogen fertilizer and control treatments over a period of 4 months. Willows were grown in rooting envelopes and harvested four times during the growing season to assess differences in allometric growth. White clover was found to increase the foliar nitrogen concentration of willow without compromising aboveground biomass. Fertilizer induced a 24% increase in total biomass of willow relative to the control. The rate of biomass allocation aboveground was greater relative to belowground under all treatments, and allometric coefficients were greater than 1.0. The differences in nitrogen uptake patterns and nitrogen use efficiencies of willow corresponded to the differences in biomass and foliar nitrogen concentrations between clones.

Keywords: Biomass partitioning; Energy crops; Rooting envelopes; *Salix*

1. Introduction

Increasing attention is being directed towards the need to develop short-rotation woody crops (SRWC) for bioenergy and bioproducts because of their positive environmental effects, ability to revitalize rural economies and enhance national

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energy security [1]. Willow shrubs (*Salix* spp.) are chosen and grown as SRWC because they are easy to propagate vegetatively, sprout vigorously when coppiced, have high biomass production, have a broad range of genetic diversity and are easy to breed [2–4]. Currently, recommendations for the establishment of SRWC involve the use of herbicides and tillage in the fall to control weeds and prepare the soil prior to planting [5]. From the time of site preparation until SRWC is planted and occupies the site (1.5 years), there is a limited amount of cover on the soil. This increases the potential for soil erosion [6–8] and non-point source pollution from SRWC [9]. There is a need to develop soil-conserving practices during establishment that will reduce soil erosion without compromising the productivity and sustainability of SRWC systems [10].

Integration and incorporation of green manure crops have been practiced in agricultural production systems to reduce runoff and soil erosion, improve soil structure through the addition of organic matter, improve soil microbial activity, infiltration rates, soil moisture availability, nutrient availability and weed suppression [11–15]. However, limited research has been conducted on integrating cover or green manure crops in SRWC systems. McLaughlin et al. [16] found that birdsfoot trefoil (*Lotus corniculatus* L.) cover crop, with the addition of nitrogen fertilizer, caused a significant increase in height in poplars (*Populus deltoides* Bartr.) relative to sole trefoil and sole native weeds cover crops. They also found that the cover crop prevented fertilizer and soil nitrogen leaching. Volk [17] found that the use of a cereal rye (*Secale cereale*) cover crop increased biomass production of poplar (*Populus nigra* × *maximowiczii*, NM6) by 85% and had no effect on willow (*S. dasyclados*, SV1) aboveground biomass production, relative to a control with no cover crop, when the cover crop was killed with a herbicide before planting SRWC. The greater aboveground biomass in poplar was attributed to the effect of cereal rye on soil moisture. The cover crop helped retain soil moisture and was found to have been a factor in higher soil water content in cover crop treatments over the entire growing season. Living cover crops integrated during establishment with various trees and woody crops were found to compete for moisture, and possibly light, resulting in reduced growth [18–20]. Malik et al. [18] found that interstate lespedeza (*Lespedeza cuneata* (Dumont) G. Don), tall fescue (*Festuca arundinacea* L.), crimson clover (*T. incarnatum*), and annual ryegrass (*Lolium multiflorum*) reduced sweetgum (*Liquidambar styraciflua* L.) biomass by 41%, 37%, 27% and 15%, respectively.

Maximizing aboveground biomass of SRWC is important from a production standpoint. In turn, the relative allocation of dry matter between the shoot and root of woody plants is a plastic feature and is dependent on site conditions as well as clonal genotype and relates to the potential to increase dry matter growth in the future. Ledig et al. [21] showed how the relative distribution of dry matter between the shoot and root of woody plants may be examined with allometry and demonstrated its use in understanding the growth of loblolly pine (*Pinus taeda*) seedlings. The coefficient of the allometric equation expresses the dynamic balance between shoot and root as it changes over time and is preferable to a simple shoot/root ratio, which changes over a growing season and during the development of a plant.

Incorporating clover into the soil as green manure is a method established in organic cropping systems [22]. The species used in this work, white clover (*Trifolium repens* L.), has been shown to accumulate between 90 and 146 $kg\,ha^{-1}$ of nitrogen when killed a year after establishment [12]. This is comparable to the annual nitrogen uptake (18–103 $kg\,ha^{-1}$) in actively growing willow [23]. However, the nitrogen demand does not depend solely on nitrogen uptake. The nitrogen use efficiency (NUE) of the woody crop is also important. *Salix sachalinensis* (SX61) and *S. discolor* (S365), two commonly deployed willow clones for SRWC in the northeastern United States, were chosen in this study to represent two levels of nitrogen use efficiencies. When grown under unirrigated field conditions with minimal nutrient inputs (100 kg N once in 3 years), the stem nutrient use efficiency of SX61 (325.9 kg biomass $kg^{-1}\,N^{-1}$) is significantly greater than the NUE for S365 (227.5 $kg\,kg^{-1}\,N^{-1}$) [24].

The objective of this study was to determine the effect of incorporating a green manure crop, white clover, on the growth rates, biomass allocation, and foliar nitrogen concentration of two clones of willow, relative to a nitrogen fertilizer and a control treatment.

2. Materials and methods

A field experiment was conducted at the Lafayette Experiment Station of the State University of New York College of Environmental Science in Syracuse, NY (42°59′50″N, 76°08′08″). The field plot was located within a fenced area to eliminate deer browsing. The soil is a Wassaic silt loam soil (Glossoboric Hapludalf, fine loamy, mixed, mesic) that is classified as well-drained [25].

The entire field experiment was 14.6×47.2 m. The experiment was laid out as a completely randomized block design with five replications. The treatment design was a 2×3 factorial. The two clones selected for this trial were *S. sachalinensis* (SX61) and *S. discolor* (S365). Both were originally obtained from the University of Toronto in the early 1990s. *S. discolor* is originally from southern Ontario while *S. sachalinensis* originated from Japan. The second factor was the three cover treatments: white clover, nitrogen fertilizer, and control, where no treatment was applied.

Site preparation began May 6, 2002 when the existing vegetation was sprayed with glyphosate (1.1 a.i. kg ha^{-1}). The site was rototilled 13 days later. The size of each plot was 8.2×14.6 m planted with 126 willow cuttings per plot.

Porous membrane rooting envelopes were used to facilitate the retrieval of entire willow root systems upon harvest. Rooting envelopes have been found to be an effective method for separating willow roots from the physical contact with soil, while still allowing for movement of water and nutrients from the external soil solution to the roots [26]. The envelopes were constructed using Versapor® nylon fabric (Pall Corporation, MI) made from hydrophilic membrane material consisting of acrylic copolymer coating over a non-woven nylon fabric with 3 μm diameter pores. Envelopes were made by folding Versapor® sheets, with dimensions of 1.07×1.63 m, in half lengthwise and sealing the long and one of the short seams with wood glue and black electrical tape. The other short seam was left open for easy insertion of willow cuttings.

Four holes in each measurement plot were excavated at a spacing of 0.91×1.50 m to a depth of 0.25 m to accommodate the rooting envelopes. Approximately 1.02 m of each rooting envelope was laid-out horizontally on the ground and the remainder with the open end was allowed to be perpendicular to the soil's surface. Soil was back-filled when the rooting membrane was in place (Fig. 1).

On May 27, 2002, a total of 1080 25-cm long dormant hardwood cuttings were planted after being soaked for 12 h. Each plot contained 16 cuttings—the middle four cuttings were inserted into the open seam of each buried rooting membrane. The envelopes were folded and sealed around the emerging cutting using staples. Buffer cuttings were planted at a spacing distance of 0.91×0.61 m. The whole experimental area was irrigated once a week with an average of 5 cm of water starting May 29, 2002.

On June 3, 2002, seeds of common Dutch white clover, pre-inoculated with rhizobial inoculant type "B", were broadcast at a rate of 10 kg ha^{-1}. Clover was mechanically killed and incorporated into the 1–10 cm of soil on June 26, 2002. Fertilizer plots were given a one-time application of ammonium nitrate (June 15, 2002) at a rate of 90 kg ha^{-1}. The amount of nitrogen from fertilization was based on matching the corresponding amount of nitrogen released from white clover.

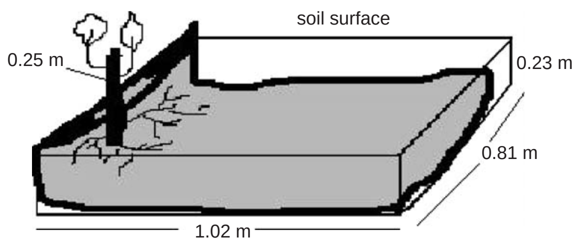

Fig. 1. The rooting envelope, beneath the surface of the soil with a willow cutting on the open end, used in a green manure study, Syracuse, NY, 2002.

Fluazifop-P-Butyl (Fusilade®, 0.45 kg active ha^{-1}) was applied to the whole experimental plot on July 31, 2002 to control grasses, which were the dominant weed on the plots. The site was irrigated biweekly during the growing season.

Out of 16 willow cuttings established per plot, destructive measurements were taken from one of the middle four ramets each month over a period of 4 months (July 30, 2002, August 15, 2002, September 10, 2002, and October 5, 2002). The soil was loosened and the rooting envelope with the entire belowground structure was removed. Each plant was then separated into roots, stems and leaves. Roots included the portion of the cutting that was belowground as well as all the roots in the envelope. Sealing the seams of the envelopes kept the roots intact, prevented roots from escaping and gave consistent results. Separated roots, stems and leaves were dried to a constant weight at 65 °C and weighed. Foliar N concentration was determined using the Kjehdahl method as detailed by Bickelhaupt and White [27]. Three replications were analyzed for foliar nitrogen concentration at each harvest.

Allometry was used to compare changes in allocation patterns over time [28,29] and logarithmic regressions of shoot, stem (shoot minus leaves), and leaf dry weight on root dry weight were compared. The model used was:

$$\ln(Y_i) = \ln a + b \ln(X_i) + \ln(e_i),$$

where Y_i is the dry weight of shoot, stem, or leaf (g) of the ith sample, X_i is the dry weight (g) of the roots for the ith sample, a is the model intercept, b is the model slope, e_i is the random error associated with estimating the ith sample, and i is any one of the samples in the data set.

Statistical analyses were performed using PROC REG and PROC GLM procedures in SAS version 8.0 [30]. Allometric regressions were tested for occurrence of parallelism and equal intercepts at $\alpha = 0.05$. Tukey's (HSD) test was used for pairwise comparison of treatment means and the slicing option for PROC GLM to test for differences between interaction LS-mean effects. Statistical significance of hypotheses was assessed at $\alpha = 0.05$ for main effects and $\alpha = 0.25$ for interaction effects [31].

3. Results

Total biomass of SX61 was significantly ($p = 0.0052$, Tables 1 and 2) and consistently greater than S365. Both clones showed little growth between the first and second harvest but biomass doubled between the second and third harvests and increased by another 60% and 64% for S365 and SX61, respectively, by the last harvest (Table 1).

There were differences in total biomass production among treatments ($p = 0.0296$) and over time ($p < 0.0001$). Total biomass of willow under the clover treatment (31.4 g) was not significantly different from the total biomass of willow under the control treatment (32.1 g) but was significantly lower than total biomass of willow under fertilization (40.0 g).

Total willow biomass was similar among the treatments at the first and second harvests, except

Table 1
Total biomass (g) for *Salix sachalinensis* (SX61) and *S. discolor* (S365), grown in a green manure study, Syracuse, NY, 2002[a]

Treatment	1st harvest			2nd harvest			3rd harvest			4th harvest		
	SX61	S365	Mean	SX61	S365	Mean	SX61	S365	Mean	SX61	S365	Mean
Control	19.9	15.2	17.6a	21.5	14.5	18.0a	39.9	26.3	33.1a	68.7	50.9	59.8a
Clover	19.3	12.9	16.1a	20.0	14.2	17.1a	41.3	32.6	37.0b	60.8	50.2	55.5b
Fertilizer	25.0	14.6	19.8b	24.1	17.0	20.6a	45.8	47.1	46.4c	77.6	68.4	73.0c
Mean	21.4	14.2		21.9	15.2		42.3	35.4		69.0	56.5	

[a]Treatments with the same letter within a given time period are not significantly different at $\alpha = 0.05$.

under the fertilizer treatment during the first harvest (Table 1). At the third harvest, total willow biomass was significantly greater under the fertilizer treatment, intermediate in the clover treatment and least in the control. By the fourth harvest, total biomass under the fertilizer treatment was significantly greater than the other two treatments and in contrast to the third harvest, total biomass under the clover treatment was significantly lower than the control.

Shoot:root allometric coefficients for control and treatments ranged from 0.97 to 1.12 for SX61 and from 1.10 to 1.19 for S365. SX61 allotted more dry matter to shoots in the rank order of fertilizer < control < clover treatments. S365 allotted dry matter with rank order of treatments, fertilizer < clover < control (Table 3). Comparing biomass equations indicated that the rates of shoot (Fig. 2, Table 4) growth were similar or coincident between clones and among the treatments, thus one line can represent all treatments within and between the two clones.

Stem biomass was proportionally the same for all treatments and for both clones with slopes, b, ranging from 1.07 to 1.17 for SX61 and 1.21 to 1.24 for S365. Slopes, b, indicate allocation of dry matter to stem relative to roots in the rank order of fertilizer < clover < control for SX61 and control < clover < fertilizer for S365. Allometric coefficients for leaf growth relative to root growth indicate slope, b, ranged from 0.81 to 1.19 for SX61 and from 0.92 to 1.15 for S365. The rates of stem and leaf growth relative to root growth were similar or coincident between clones and among the treatments, thus one line can represent all treatments within and between the two clones.

Average foliar nitrogen concentration for willow between treatments ranged from 18.2 to 21.0 $g\,kg^{-1}$. Clonal differences between willows showed that SX61 consistently had greater foliar nitrogen concentration compared to S365 ($p = 0.0040$, Tables 5 and 6). Main effects revealed that foliar nitrogen concentration for both clones under fertilization (21.0 $g\,kg^{-1}$) was similar to the clover treatment (20.0 $g\,kg^{-1}$) and significantly greater than the control (18.2 $g\,kg^{-1}$). Foliar nitrogen concentrations for both clones across the four harvests ($p = 0.0484$, Table 6) were significantly greater under fertilization (Table 5) at the first harvest but not in the subsequent harvests. Foliar nitrogen concentration of willow under the clover treatment was significantly greater relative to the control (Table 5) at the first and second harvests but not at third and fourth harvests.

Table 2
Mean square and p-values from ANOVA for total biomass (g) for *Salix sachalinensis* (SX61) and *S. discolor* (S365) ramets, grown in a green manure study, Syracuse, NY

Source	df	MS	p-value
Block	4	454.3	0.0057
Clone	1	2088.0	0.0052
Cover	2	897.7	0.0296
Clone*cover	2	50.7	0.7900
Block(clone*cover)	20	212.6	0.0292
Time	3	13,503.0	< 0.0001
Clone*time	3	59.5	0.6687
Cover*time	6	157.4	0.2345
Clone*cover*time	6	55.7	0.8154
Error	72	114.1	

Table 3
Coefficients for $\ln y = a + b \ln x$ for shoot on root dry weight of *Salix sachalinensis* (SX61) and *S. discolor* (S365) in a green manure study, Syracuse, NY, 2002

Clone treatment	N	a	b	R^2	$S_{y.x}$, g
SX61					
Control	20	−0.18	1.09	0.74	0.36
Clover	20	−0.24	1.12	0.73	0.37
Fertilizer	20	0.33	0.97	0.81	0.28
S365					
Control	20	−0.56	1.19	0.86	0.29
Clover	20	−0.38	1.13	0.77	0.39
Fertilizer	20	−0.13	1.10	0.91	0.24

4. Discussion

Total biomass of willow was not affected by the white clover green manure crop until the end of the growing season. Four-week-old clover just started to develop nodules when they were turned under. Fertilization, on the other hand, increased total biomass by 24% relative to the control. Over the

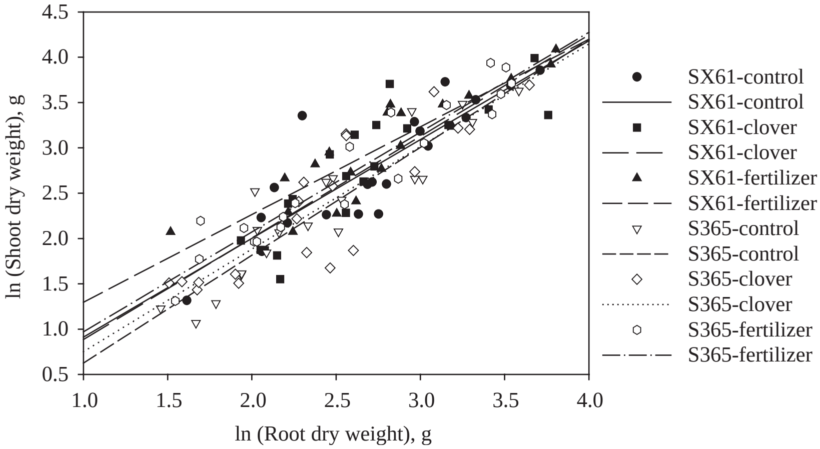

Fig. 2. Allometric regressions of ln (shoot) on ln (root dry weight) for *Salix sachalinensis* (SX61) and *S. discolor* (S365) and three different cover treatments (white clover, fertilizer, control), in a green manure study, Syracuse, NY, 2002.

Table 4
P-values from *t*-tests done to test parallelism and equal intercepts between treatments within clones and between treatments for *Salix sachalinensis* (SX61) and *S. discolor* (S365), in a green manure study, Syracuse, NY, 2002

	$H_0{:}\beta_3 = 0$	$H_0{:}\beta_2 = 0$
Within clones		
SX61		
Control vs. clover	0.84	0.92
Control vs. fertilizer	0.27	0.18
Clover vs. fertilizer	0.19	0.14
S365		
Control vs. clover	0.69	0.79
Control vs. fertilizer	0.27	0.11
Clover vs. fertilizer	0.18	0.10
Between treatments		
Control vs. clover	0.73	0.82
Control vs. fertilizer	0.87	0.92
Clover vs. fertilizer	0.93	0.80

growing season, both clones exhibited periods of rapid growth—doubling in total biomass between the second and third harvests and further growing 60–64% by the last harvest. The time difference between the first and second harvests was only 2 weeks, thus no distinct change was obvious. Similar responses were found when stem volumes of hybrid poplars grew 24–35% greater in the first year when fertilized with either readily soluble or controlled-released nitrogen at planting [32]. The differences in nitrogen uptake patterns and nitrogen use efficiencies of willow corresponded to the differences in biomass between clones. SX61 had greater biomass and faster rates of growth compared to S365 under all cover treatments. Since SX61 has a higher nitrogen efficiency ratio (325.9 kg biomass kg^{-1} N^{-1}) than S365 (227.5 kg kg^{-1}) [24], SX61's response was expected, especially under the fertilizer treatment.

In terms of dry matter allocation, both willow clones allocated more dry matter aboveground (shoot) relative to belowground structures. Aboveground biomass was more responsive to the fertilizer treatment compared to the clover treatment with the rank order of clover < control < fertilizer. Further breakdown of shoot development showed significant increase in dry matter allocation to stems for SX61 in the control and fertilizer treatments, and with all treatments for S365, relative to roots. With the same amount of dry matter, biomass appears to be allocated more into stem growth rather than leaf production, relative to root growth, especially for S365.

For both SX61 and S365 the relative growth rate of the shoot was greater than that of the root during the first growing season. Allometric coefficients greater than 1.0, in this study as high as 1.2, indicate that more dry matter is being allocated to

Table 5
Mean foliar nitrogen concentration ($g\,kg^{-1}$) for *Salix sachalinensis* (SX61) and *S. discolor* (S365), green manure study, Syracuse, NY, 2002[a]

Treatment	1st harvest			2nd harvest			3rd harvest			4th harvest		
	SX61	S365	Mean	SX61	S365	Mean	SX61	S365	Mean	SX61	S365	Mean
Control	10.1	10.8	10.4a	16.3	17.2	16.8a	24.3	21.6	23.0a	23.9	21.6	22.7a
Clover	18.6	14.9	16.7b	22.8	15.8	19.3b	23.9	18.4	21.2a	23.5	21.8	22.7a
Fertilizer	24.6	17.9	21.3c	17.3	18.2	17.8ab	25.9	19.9	22.9a	23.2	20.9	22.1a
Mean	17.8	14.5		18.8	17.1		24.7	20.0		23.5	21.4	

[a]Treatments with the same letter within a given time period are not significantly different at $\alpha = 0.05$.

Table 6
Mean square and *p*-values from ANOVA for foliar nitrogen concentration ($g\,kg^{-1}$) for *Salix sachalinensis* (SX61) and *S. discolor* (S365) ramets, green manure study, Syracuse, NY, 2002

Source	df	MS	*p*-value
Block	2	1.0	0.0160
Clone	1	1.6	0.0040
Cover	2	0.5	0.0476
Clone*cover	2	0.2	0.2031
Block(clone*cover)	10	0.3	0.8429
Time	3	1.8	0.0002
Clone*time	3	0.1	0.7580
Cover*time	6	0.5	0.0484
Clone*cover*time	6	0.1	0.7482
Error	36	0.1	

shoot growth than to root growth and that shoot:root ratios, therefore, were increasing during the first year. However, previous studies of allometric growth of woody plants have indicated that for the first year of growth, at least, allometric coefficients, k (in this study, b), are much less than 1.0. Past work with *Populus trichocarpa* ($k = 0.77-0.97$) [33], *P. deltoides* ($k = 0.42-0.55$) [34], and with six deciduous species (measured shoot:root ratios declined in four *Quercus* species, *Prunus serotina* and *Liriodendron tulipifera*, implying $k < 1.0$) [35], shows that early developmental growth of woody dicots favors dry matter allocation to roots rather than to shoots. In these studies, allometric coefficients were always less than 1.0 and shoot:root ratios decreased in the first year. A reanalysis of data of Drew [26], who grew *S. purpurea* clonal material for 2 and 4 months in separate one year studies indicates that willow plants grown outside with minimal watering and no fertilizer had allometric coefficients as low as 0.03 and were preferentially allocating large amounts of dry matter to root growth. The present study stands as an anomaly in the light of past examples where dry matter allocation has been followed and allometric growth favored roots in the first year.

An explanation for an increasing shoot:root ratio, may lie in the selection and management practices followed for willow clones SX61 and S365. Both the clones used in this experiment may be ones that have exceptionally high rates of genetically based shoot growth and this is reflected in their relative growth rates. Clone S365, from southern Ontario, was screened against hundreds of other clones and selected for its good aboveground growth potential. Clone SX61, from Asia, likewise was screened from many others and picked because of its superior aboveground biomass production.

Alternatively, the willow clones used may have a high degree of phenotypic plasticity that causes the allocation of dry matter to shoots and roots to vary with growing conditions. Aboveground allocation of biomass to stem, leaf and branch growth of trees has been shown to be favored by high soil nitrogen availability and when soil nitrogen is low, carbohydrate allocation to fine roots of trees is favored [36–38]. Similar responses have also been observed in response to water stress [39,40]. Further, mycorrhizal development and fine root production is greater in low fertility soils [41].

Thornley's model [42] accounts for the dynamic balance between shoot and root growth in trees. If fertilization was a significant factor in allocation, then there should have been a significant difference between the fertilizer and control treatments. The lack of response to nitrogen may be due to the nitrogen that was mineralized from the organic matter from the weeds that were turned under at the beginning of the growing season. Previous studies [38,43] indicated that under low nitrogen, nitrogen was the limiting factor whereas under high nitrogen treatment, water availability becomes the limiting factor for growth and production of poplar and willow. The willow clones used in this study were given both ample water and nitrogen additions, interactive conditions that may have promoted shoot growth at the expense of root growth.

If selection practices are promoting the use of clones with high shoot allometric growth, i.e., with $b \geqslant 1.0$, these clones may be at a genetic disadvantage on dry soils or soils of low nutrient availability. If phenotypic plasticity accounts for the results reported here, then the clones may be successful under adverse moisture or fertility regimes, but produce less aboveground biomass. In five unirrigated trials across the northeastern US, the first rotation yield of SX61 was always greater than S365 [44]. The yield of SX61 (6.9–12.3 odt ha^{-1} yr^{-1}) and S365 (1.6–8.0 odt ha^{-1} yr^{-1}) varied widely depending on site (soils and weed competition primarily) and weather conditions, which covered a large range in these trials. This suggests that these clones are sensitive to site and weather conditions. Despite the variation in yield, SX61 was always ranked in the top three clones in all the trials, while the ranking of S365 ranged from 4th–11th. Relative to S365, and other willow clones used for biomass production, SX61 may be more plastic across a range of sites. Whether or not this is true, and where the balance lies between genetics and environmental influences for specific clones, may be determined through experimentation.

Foliar N concentration increased significantly under the clover treatment for the first 2 months of growth before leveling off thereafter. Likewise, foliar N concentration significantly increased with fertilization, but leveled off for both clones after only a month's growth. Although foliar nitrogen concentrations of willow obtained under the clover and fertilizer treatments were found to be below the optimum range of 3–4% [45], it was clear that using white clover as a green manure or application of a nitrogen fertilizer, increased foliar nitrogen concentrations for willow. Clover killed and incorporated hastened decomposition of plant residues and probably enhanced soil aeration. Upon death of a legume, soil bacteria consume the new and abundant source of simple sugars and proteins. Soil bacteria populations proportionally increase in numbers and thereby increase the rate of decomposition of the green manure [12]. Although it is difficult to control and foresee the nitrogen mineralization pattern, high amounts of nitrogen from clover are generally mineralized within a month following incorporation [46,47]. The leveling off of foliar nitrogen concentrations towards the end of the season, for both willow clones, may be due to various factors. The porous membrane envelopes forced the willow roots to grow along a horizontal plane, which might have limited mineralized nitrogen capture especially if and when irrigation promoted leaching of mineralized nitrogen below the depth by which the roots were present. Also, foliar nitrogen concentration usually peaks in mid- to late-August then declines as nitrogen is withdrawn from leaves and retranslocated back into buds, photosynthetic stems and roots before leaf abscission in autumn [48].

Potential for soil erosion and non-point source pollution during the establishment of SRWC is a concern. Integrating and managing green manures in SRWC may be helpful in the development of this system to address these issues. Systems can be developed to increase cover on the soil surface to reduce soil erosion and weeds while maintaining moisture and organic matter in soils. Approaches that may improve the system include early establishment of the green manure, allowing it to remain for a longer period of time before incorporation, using other green manures or combinations of species, or leaving residue on the soil surface to act more like a cover crop.

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